

# Z PENGUINS AND RARE B DECAYS

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Rare  $B$  decays of the type  $b \rightarrow s \ell^+ \ell^- (\nu \bar{\nu})$  are analyzed in a generic scenario where New Physics effects enter predominantly via  $Z$  penguin contributions. We show that this possibility is both phenomenologically allowed and well motivated on theoretical grounds. The important role played in this context by the lepton forward-backward asymmetry in  $B \rightarrow K^* \ell^+ \ell^-$  is emphasized.

## 1 Introduction

Flavour-changing neutral-current (FCNC) processes provide a powerful tool in searching for clues about non-standard flavour dynamics. Being generated only at the quantum level and being additionally suppressed, within the Standard Model (SM), by the smallness of the off-diagonal entries of the Cabibbo-Kobayashi-Maskawa (CKM) matrix,<sup>1</sup> their observation is very challenging. This suppression, however, ensures a large sensitivity to possible non-standard effects, even if these occur at very high energy scales, rendering their experimental search highly valuable.

In the present talk we focus on a specific class of non-standard  $\Delta B = 1$  FCNC transitions: those mediated by the  $Z$ -boson exchange and contributing to rare  $B$  decays of the type  $b \rightarrow s \ell^+ \ell^- (\nu \bar{\nu})$ . As we shall show, these are particularly interesting for two main reasons: i) there are no stringent experimental bounds on these transitions yet; ii) it is quite natural to conceive extensions of the SM where the  $Z$ -mediated FCNC amplitudes are substantially modified, even taking into account the present constraints on  $\Delta B = 2$  and  $b \rightarrow s \gamma$  processes.

In a generic extension of the Standard Model where new particles appear only above some high scale  $M_X > M_Z$ , we can integrate out the new degrees of freedom and generate a series of local FCNC operators already at the electroweak scale. Those rel-

evant for  $b \rightarrow s \ell^+ \ell^- (\nu \bar{\nu})$  transitions can be divided into three wide classes: generic dimension-six operators, magnetic penguins and FCNC couplings of the  $Z$  boson.<sup>2</sup> The latter are dimension-four operators of the type  $\bar{b}_{L(R)} \gamma^\mu s_{L(R)} Z_\mu$ , that we are allowed to consider due to the spontaneous breaking of  $SU(2)_L \times U(1)_Y$ . Their coefficients must be proportional to some symmetry-breaking term but do not need to contain any explicit  $1/M_X$  suppression for dimensional reasons, contrary to the case of dimension-six operators and magnetic penguins. This naive argument seems to suggest that FCNC couplings of the  $Z$  boson are particularly interesting and worth to be studied independently of the other effects. It should be noticed that the requirement of naturalness in the size of the  $SU(2)_L \times U(1)_Y$  breaking terms implies that also the adimensional couplings of the non-standard  $Z$ -mediated FCNC amplitudes must vanish in the limit  $M_X/M_Z \rightarrow \infty$ . Nonetheless, as we will illustrate below with an explicit example, the above naive dimensional argument remains a strong indication of an independent behaviour of these couplings with respect to the other FCNC amplitudes.

## 2 FCNC $Z$ penguins in generic SUSY models

An explicit example where the largest deviations from the SM, in the sector of FCNC, are generated by the  $Z$  boson exchange can be

realized within supersymmetric models with generic flavour couplings. Within this context, assuming  $R$  parity conservation and minimal particle content, FCNC amplitudes involving external quark fields turn out to be generated only at the quantum level. Moreover, assuming the natural link between trilinear soft-breaking terms and Yukawa couplings, sizable  $SU(2)_L$ - and flavour-breaking effects can be expected in the up sector due to the large Yukawa coupling of the third generation. Thus the potentially dominant non-SM effects in the effective  $Z\bar{b}s$  vertex turn out to be generated by chargino-up-squarks loops and have a pure left-handed structure, like in the SM.<sup>3</sup>

Similarly to the  $Z\bar{s}d$  case,<sup>4</sup> the first non-vanishing contribution appears to the second order in a simultaneous expansion of chargino and squark mass matrices in the basis of electroweak eigenstates. The potentially largest effect arises when the necessary  $SU(2)_L$  breaking ( $\Delta I_W = 1$ ) is equally shared by the  $\tilde{t}_R - \tilde{u}_L^s$  mixing and by the chargino-higgsino mixing, carrying both  $\Delta I_W = 1/2$ . For a numerical evaluation, normalizing the SUSY result to the SM one (evaluated in the 't Hooft-Feynman gauge) and varying the parameters in the allowed ranges, leads to:<sup>2,3</sup>

$$\left| \frac{Z_{sb}^{\text{SUSY}}}{Z_{sb}^{\text{SM}}} \right| \lesssim \frac{0.1}{|V_{ts}|} \left| \frac{(M_U^2)_{t_R s_L}}{M_{\tilde{u}_L}^2} \right| \left( \frac{M_W}{M_2} \right) \\ = 2.5 |(\delta_{RL}^U)_{32}| \left( \frac{M_W}{M_2} \right). \quad (1)$$

The coupling  $(\delta_{RL}^U)_{32}$ , which represents the analog of the CKM factor  $V_{ts}$  in the SM case, is not very constrained at present and can be of  $\mathcal{O}(1)$  with an arbitrary  $CP$ -violating phase. Note, however, that vacuum stability bounds<sup>5</sup> imply  $|(\delta_{RL}^U)_{32}| \lesssim \sqrt{3}m_t/M_S$ , where  $M_S$  denotes the generic scale of sparticle masses. Therefore the SUSY contribution to the  $Z$  penguin decouples as  $(M_Z/M_S)^2$  in the limit  $M_S/M_Z \rightarrow \infty$ .

As it can be checked by the detailed analysis of Lunghi *et al.*,<sup>3</sup> in the interesting sce-

nario where the left-right mixing of up-type squarks is the only non-standard source of flavour mixing,  $Z$  penguins are largely dominant with respect to other supersymmetric contributions to  $b \rightarrow s \ell^+ \ell^-$ . Indeed, due to the different  $SU(2)_L$  structure, the  $\tilde{t}_R - \tilde{u}_L^s$  mixing contributes to magnetic penguins only to the third order in the mass expansion discussed above. Therefore in this scenario the magnetic-penguin contribution to  $b \rightarrow s \ell^+ \ell^-$  is additionally suppressed by  $M_Z/M_S$  with respect to the  $Z$ -penguin one. Similarly, in the case of box diagrams the  $\tilde{t}_R - \tilde{u}_L^s$  mixing alone leads to a contribution that decouples like  $M_Z^4/M_S^4$ .

### 3 Experimental bounds on the $Z\bar{b}s$ vertex

An extended discussion of other non-standard scenarios where large deviations from the SM occur in the  $Z\bar{b}s$  vertex can be found elsewhere.<sup>2</sup> We proceed here analyzing the experimental information on this FCNC amplitude in a model-independent way.

The dimension-four effective FCNC couplings of the  $Z$  boson relevant for  $b \rightarrow s$  transitions can be described by means of the following effective Lagrangian

$$\mathcal{L}_{FC}^Z = \frac{G_F}{\sqrt{2}} \frac{e}{\pi^2} M_Z^2 \frac{\cos \Theta_W}{\sin \Theta_W} Z^\mu \\ \times (Z_{sb}^L \bar{b}_L \gamma_\mu s_L + Z_{sb}^R \bar{b}_R \gamma_\mu s_R) + \text{h.c.}, \quad (2)$$

where  $Z_{sb}^{L,R}$  are complex couplings. Evaluated in the 't Hooft-Feynman gauge, the SM contribution to  $Z_{sb}^{L,R}$  is given by

$$Z_{sb}^R|_{\text{SM}} = 0, \quad Z_{sb}^L|_{\text{SM}} = V_{tb}^* V_{ts} C_0(x_t), \quad (3)$$

where  $x_t = m_t^2/m_W^2$  and  $C_0(x)$  is a loop function<sup>6,7</sup> of  $\mathcal{O}(1)$ . Although  $Z_{sb}^L|_{\text{SM}}$  is not gauge invariant, we recall that the leading contribution to both  $b \rightarrow s \ell^+ \ell^-$  and  $b \rightarrow s \nu \bar{\nu}$  amplitudes in the limit  $x_t \rightarrow \infty$  is gauge independent and is generated by the large  $x_t$  limit of  $Z_{sb}^L|_{\text{SM}}$  ( $C_0(x_t) \rightarrow x_t/8$  for  $x_t \rightarrow \infty$ ).

Constraints on  $|Z_{sb}^{L,R}|$  can be obtained from the experimental upper bounds on exclusive and inclusive  $b \rightarrow s \ell^+ \ell^- (\nu \bar{\nu})$  transitions. The latter are certainly more clean from the theoretical point of view (especially the  $b \rightarrow s \nu \bar{\nu}$  one<sup>8</sup>) although their experimental determination is quite difficult. At present the most significant information from exclusive decays is given by<sup>9</sup>  $\mathcal{B}(B \rightarrow X_s \ell^+ \ell^-) < 4.2 \times 10^{-5}$  and leads to<sup>2</sup>

$$\left(|Z_{sb}^L|^2 + |Z_{sb}^R|^2\right)^{1/2} \lesssim 0.15. \quad (4)$$

Within exclusive channels the most stringent information can be extracted from  $B \rightarrow K^* \mu^+ \mu^-$ , where the experimental upper bound<sup>10</sup> on the non-resonant branching ratio ( $\mathcal{B}^{\text{n.r.}} < 4.0 \times 10^{-6}$ ) lies only about a factor two above the SM expectation.<sup>11</sup> Taking into account the uncertainties on the hadronic form factors, this implies<sup>2</sup>

$$|Z_{bs}^{L,R}| \lesssim 0.13. \quad (5)$$

Additional constraints on the  $Z_{bs}^{L,R}$  couplings could in principle be obtained by the direct limits on  $\mathcal{B}(Z \rightarrow b \bar{s})$  and by  $B_s - \bar{B}_s$  mixing, but in both cases these are not very significant.

Interestingly the bounds (4-5) leave open the possibility of large deviations from the SM expectation in (3). In the optimistic case where  $Z_{bs}^L$  or  $Z_{bs}^R$  were close to saturate these bound, we would be able to detect the presence of non-standard dynamics already by observing sizable rate enhancements in the exclusive modes. In processes like  $B \rightarrow K^* \ell^+ \ell^-$  and  $B \rightarrow K \ell^+ \ell^-$ , where the standard photon-penguin diagrams provide a large contribution, the enhancement could be at most of a factor 2-3. On the other hand, in processes like  $B \rightarrow K^* \nu \bar{\nu}$ ,  $B \rightarrow K \nu \bar{\nu}$  and  $B_s \rightarrow \ell^+ \ell^-$ , where the photon-exchange amplitude is forbidden, the maximal enhancement could reach a factor 10.

#### 4 Forward-backward asymmetry in $B \rightarrow K^* \mu^+ \mu^-$

If the new physics effects do not produce sizable deviations in the magnitude of the  $b \rightarrow Z^* s$  transition, it will be hard to detect them from rate measurements, especially in exclusive channels. A much more interesting observable in this respect is provided by the forward-backward (FB) asymmetry of the emitted leptons, also within exclusive modes. In the  $\bar{B} \rightarrow \bar{K}^* \mu^+ \mu^-$  case this is defined as

$$\mathcal{A}_{FB}^{(\bar{B})}(s) = \frac{1}{d\Gamma(\bar{B} \rightarrow \bar{K}^* \mu^+ \mu^-)/ds} \int_{-1}^1 d\cos\theta \frac{d^2\Gamma(\bar{B} \rightarrow \bar{K}^* \mu^+ \mu^-)}{ds d\cos\theta} \text{sgn}(\cos\theta), \quad (6)$$

where  $s = m_{\mu^+ \mu^-}^2 / m_B^2$  and  $\theta$  is the angle between the momenta of  $\mu^+$  and  $\bar{B}$  in the dilepton center-of-mass frame. Assuming that the leptonic current has only a vector (V) or axial-vector (A) structure, then the FB asymmetry provides a direct measure of the A-V interference. Since the vector current is largely dominated by the photon-exchange amplitude and the axial one is very sensitive to the Z exchange,  $\mathcal{A}_{FB}^{(\bar{B})}$  and  $\mathcal{A}_{FB}^{(B)}$  provide an excellent tool to probe the  $Z\bar{b}s$  vertex.

Employing the usual notations for the Wilson coefficients of the SM effective Hamiltonian relevant to  $b \rightarrow s \ell^+ \ell^-$  transitions,<sup>7</sup>  $\mathcal{A}_{FB}^{(\bar{B})}(s)$  turns out to be proportional to<sup>a</sup>

$$\text{Re} \left\{ C_{10}^* \left[ s C_9^{\text{eff}}(s) + \alpha_+(s) \frac{m_b C_7}{m_B} \right] \right\}, \quad (7)$$

where  $\alpha_+(s)$  is an appropriate ratio of hadronic form factors.<sup>2,12</sup> The overall factor ruling the magnitude of  $\mathcal{A}_{FB}^{(\bar{B})}(s)$  is affected by sizable theoretical uncertainties. Nonetheless there are at least three features of this observable that provide a clear short-distance information:

i) Within the SM  $\mathcal{A}_{FB}^{(\bar{B})}(s)$  has a zero in the low  $s$  region ( $s_0|_{\text{SM}} \sim 0.1$ ).<sup>12</sup> The exact

<sup>a</sup> To simplify the notations we have introduced the parameter  $C_9^{\text{eff}}(s)$  that is not a Wilson coefficient but it can be identified with  $C_9$  at the leading-log level.<sup>2</sup>

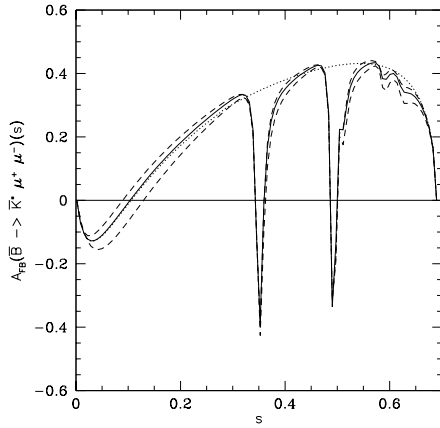


Figure 1.  $FB$  asymmetry of  $\bar{B} \rightarrow \bar{K}^* \mu^+ \mu^-$  within the SM. The solid (dotted) curves have been obtained employing the Krueger-Sehgal<sup>14</sup> approach (using the perturbative end-point effective Hamiltonian<sup>2</sup>). The dashed lines show the effect of varying the renormalization scale of the Wilson Coefficients between  $m_b/2$  and  $2m_b$ , within the Krueger-Sehgal approach.

position of  $s_0$  is not free from hadronic uncertainties at the 10% level, nonetheless the existence of the zero itself is a clear test of the relative sign between  $C_7$  and  $C_9$ . The position of  $s_0$  is essentially unaffected by possible new physics effects in the  $Z\bar{b}s$  vertex.

ii) The sign of  $\mathcal{A}_{FB}^{(\bar{B})}(s)$  around the zero is fixed unambiguously in terms of the relative sign of  $C_{10}$  and  $C_9$ :<sup>2</sup> within the SM one expects  $\mathcal{A}_{FB}^{(\bar{B})}(s) > 0$  for  $s > s_0$ , as in Fig. 1. This prediction is based on a model-independent relation among the form factors<sup>13</sup> that has been overlooked in most of the recent literature. Interestingly, the sign of  $C_{10}$  could change in presence of a non-standard  $Z\bar{b}s$  vertex leading to a striking signal of new physics in  $\mathcal{A}_{FB}^{(\bar{B})}(s)$ , even if the rate of  $\bar{B} \rightarrow \bar{K}^* \ell^+ \ell^-$  was close to its SM value.

iii) In the limit of  $CP$  conservation one expects  $\mathcal{A}_{FB}^{(\bar{B})}(s) = -\mathcal{A}_{FB}^{(B)}(s)$ . This holds at the per-mille level within the SM, where  $C_{10}$  has a negligible  $CP$ -violating phase, but again it could be different in presence of new physics in the  $Z\bar{b}s$  vertex. In this case the

ratio  $[\mathcal{A}_{FB}^{(\bar{B})}(s) + \mathcal{A}_{FB}^{(B)}(s)]/[\mathcal{A}_{FB}^{(\bar{B})}(s) - \mathcal{A}_{FB}^{(B)}(s)]$  could be different from zero, for  $s$  above the charm threshold, reaching the 10% level in realistic models.<sup>2</sup>

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